STUDIES FOR STUDENTS[1]

RELATIVE GEOLOGICAL IMPORTANCE OF CONTINENTAL, LITTORAL, AND MARINE SEDIMENTATION

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PART II

THE REGIONS OF MARINE SEDIMENTATION

For the present purpose it is unnecessary to consider the deep ocean deposits, or even the massive limestone formations, since the discussion centers on the comparison of the areal extent and importance of the detrital deposits upon the land and beneath the sea.

The investigations of the Challenger expedition[2] showed that the rubble, sand, and silt were practically limited to the upper 100 fathoms of the ocean bed, and that this corresponded rather closely with the limits of the continental shelves. At about this depth the bottom is in general rarely disturbed by the action of currents or waves. Except in bays, fjords, and inclosed seas where mud is met with in shallow water, it may be said that in general, fronting all

[1] Continued from p. 356.

[2] Murray, *Deep Sea Deposits*, p. 184.

open coasts, 100 fathoms is the average depth at which fine mud or ooze commences to form; but local exceptions may be noted. In general, the cleaner sands are restricted to a belt within 30 miles of shore, and the average limit of the blue muds is about 200 miles, though this varies greatly in different regions. The relation of these terrigenous to the true pelagic deposits is well brought out in Chart I, *Deep Sea Deposits*, Challenger Expedition. This area of marine deposits of land-waste is etimated to cover about one-seventh of the globe and to be equal to half the area of the continents, while the area within the 100-fathom line, which more immediately concerns the present subject, is estimated at 10,000,000 square miles, or about one-fifth of the continental areas.

The deposits of former ages corresponding to the shallower and deeper portions of the terrigenous zone may be distinguished by a number of textural and structural features. For instance, considering the conditions of present deposition, it is seen that the ancient equivalents of the present blue muds will be rather widely extended, uniform, massive, argillaceous deposits, usually slightly carbonaceous and grading into calcareous formations. They will be without cross-bedding and ripple-marks, since movements sufficient to form these would prevent the settling of muds. They may be distinguished from ancient estuarine muds by all these features, and especially the absence of frequent alternations of sand. It is doubtful, however, if the deeper portions of these blue muds have ever been elevated into land surfaces. On the other hand, the shallower belt of marine deposition will be marked by a sandy character of deposits, provided that the rocks of the land can furnish sand, by evidences of shifting current-action and by ripple-marks. A. R. Hunt has shown that the waves of storms may stir the sands of the bottom to a depth of 40 fathoms sufficiently to move gravel and injure living molluscs.[1]

The charts of the United States Coast and Geodetic Survey also show sand and comminuted shells to similar depths, from which it may be inferred that widespread arenaceous and unfossiliferous formations may be formed on the bottoms of shallow seas, and not necessarily in close proximity to the littoral zone.

[1] "On the Formation of Ripple Marks," *Proceedings of the Royal Society of London*, Vol. XXXIV (1882), p. 1.

Approaching the shore, the material of the shallow bottom becomes coarser and ends in the undertow slope of the beach. This is sometimes coarser than the material of the beach itself,[1] stones of a certain size being swept here by the undertow and only carried back to the beach by the heavier storms. It is to be concluded, therefore, that one of the most striking characteristics of ancient beach-action, a basal conglomerate, is hardly so much a mark of littoral deposition as of marginal marine deposition *bordering* the true littoral zone.

As river deposits of delta surfaces, on the one hand, tend to extend themselves both by building forward into the sea and by building backward over the land, so, on the other hand, marine deposits, as Chamberlin has pointed out, tend to extend themselves in both directions.[2] Toward the deep ocean basins the clays are swept and deposited near their brink, doubtless building out submarine deltas, as is suggested by the submarine platforms of the Caribbean Sea.[3] and by the hypsographic curve of the earth crust given by Penck.[4] In the opposite direction the waves are always at work upon the coast, and tend to cut the sea-cliff landward, except where the supply of material from the land is equal to that removed by the sea. As the wave-beaten material is rolled backward and forward, it is gradually reduced to a fineness where the undertow can sweep it away from the beach-action and allow it to finally settle at some little distance from the land. The result of these activities within the upper portions of the ocean is to cut back all headlands, to fill up recessions in the coast line, and to cut away all islands except where these have been thrown up as barrier beaches by the sea.

The rapidity with which the waves may cut into unconsolidated material has been frequently illustrated by the destruction of recent ash-cones, which in a few months or years have completely disappeared. Barrier beaches, the only form of islands tolerated by the sea, are thrown up where the waves drag and break in shallow

[1] Dana, *Manual of Geology*, p. 223.

[2] T. C. Chamberlin, "The Ulterior Basis of Time Divisions," *Journal of Geology*, Vol. VI (1898), p. 454.

[3] Bailey Willis, "Conditions of Sedimentary Deposition," *Journal of Geology*, Vol, I (1893), pp. 496, 497.

[4] *Morphologie der Erdoberfläche*, Vol. I (1894), p. 136.

water, and can attain any degree of permanence only where they face a gently shelving land mass.

The waves not only tend to unify and extend the shallow submarine platform, but tend to cut away its highest portions to a certain depth, dependent upon the power of the waves. Thus, by taking nautical charts it is observed that over any district where there is open water the bottom maintains a certain depth close up to the off-shore beach. Facing the open oceans this is usually from 30 to 40 feet, but in more protected places, such as Long Island Sound, it may be but 6 to 12 feet. Thus, up to the line of surf the submarine platform extends without any confusion with the littoral zone.

EXTENT AND CHARACTER OF THE LITTORAL ZONE

The littoral region, as has been shown, is rather sharply delimited from the marine by the trimming action of the sea, marked along a shelving shore by the line of barrier beaches. Where a bold land meets the sea, it is merely the lowest exposed portion of the sea-cliff. On the landward side, however, the littoral is not so regularly defined, but consists of irregular tidal lagoons consisting of three portions; the mud-flats, exposed at low tide, the salt marshes flooded only at high tide, and a rather abrupt transitional mud-slope between them. Both the mud-flats and tidal marshes are cut through by tidal channels, those on the marsh being characterized by meanders.

The littoral finds its greatest development in estuaries or where the land meets the sea in the form of a plain, either a base-plain of erosion, or a river plain of aggradation. The littoral does not show a tendency, like the two previous regions, to extend its limits, since the flood-tide tends to leave sediment upon the tidal marshes, building them up to the extreme tidal limit; and, on the other hand, the tidal scour of ebb-tide tends to remove sediment to the open sea. On the contrary, the forces of both land and sea tend to fill up and obliterate the littoral. On the one hand, the river deposits and the wash from the land creep out over the tidal flats, and, on the other, the sea, by wearing the beach deposits smaller and by removing the finer shore material outward to a greater depth, tends to push its beaches farther inland.

The littoral zone is partly maintained by the contest of the two

forces—the rivers building out by irregular delta mouths, inclosing lagoons and providing new tidal marshes; the sea cutting off headlands and sweeping the material along the coast, forming spits which shut off new lagoon spaces.

The chief maintenance of the littoral belt is, however, due to vertical land movements, especially subsidence of a flat land surface, but one still showing slight relief. This may produce extensive estuaries, and the waves, by throwing up barrier beaches in shallow water at some distance from the land, may form a continuous series of lagoons and salt marshes, as is illustrated by the present condition of the seaward margin of the coastal plain of the eastern United States from Long Island southward. The questions of immediate importance in the present connection are those of the width and areal extent of the littoral zone and possible fluctuations in importance in past times, owing to the prevalence of conditions not now operative, such as absence of tides in ancient protected seas, or hypothetically greater oceanic tides due to a possibly greater nearness of the moon. It is first necessary to collect the facts for the argument, by observing the various shore conditions as they exist today. Arranging these with respect to the tidal range, a representative set is as follows, the information being taken largely from the charts of the United States Coast and Geodetic Survey:

OBSERVED RELATION OF TIDES TO THE LITTORAL ZONE

TIDE 1 TO 1.5 FEET (EXAM. MOBILE BAY AND MISSISSIPPI DELTA, GULF OF MEXICO; STORM TIDES THE ONLY IMPORTANT ONES)

Mud-flats at mean low tide, 0.1 to 0.25 mile wide in protected places.

Salt marshes.—Frequently absent. Around Mobile Bay a few up to 2 miles wide. On the delta of the Mississippi (General Chart No. 19) they average 27 miles in width, cut through by the fresh-water channels and showing a poorly developed system of channels for tidal drainage.

TIDE 2.5 FEET (EXAM. GARDINER'S ISLAND AND OYSTER PONDS)

Mud-flats few in number. At mean low tide 0.33 to 0.66 mile wide in protected places.

Salt marshes average 0.25 mile wide.

TIDE 4 TO 6 FEET (VICINITY OF NEW YORK AND NEW HAVEN)

Mud-flats from 0.16 to 0.33 mile wide, of limited development.

Salt marshes in protected inlets behind barrier beaches 0.5 to 1.0 mile wide.

Along river valleys, as north of Newark Bay, they extend some 3 miles from the open water, passing into the fresh-water marshes. Tidal channels fairly well developed upon marshes.

TIDE 7 FEET (SAVANNAH, GA., ENTRANCE TO SAVANNAH RIVER)

Mud-flats 0.33 to 0.66 mile wide. More commonly present than in previous examples.

Salt marshes filling up a former estuary, 4 to 5 miles wide, with a well-developed network of tidal channels ramifying through them.

TIDE 10 FEET (BOSTON HARBOR AND DELTA OF THE INDUS RIVER)

Mud-flats extensive. At Boston they average from 0.5 to 1.0 mile wide, but are cut up by tidal scour into smaller separated areas.

Salt marshes.—At Boston, filling up protected depressions, they average 0.25 to 0.75 mile wide. On the Indus delta a well-developed network of tidal channels, 2 to 4 fathoms deep, and distinct from the distributaries of the river, extends 17 miles from the coast, and this may be taken as the limit at which the salt-water tidal marsh gives place to the fresh-water swamp. Tide reaches 11 feet in spring tides.

TIDE 16 FEET (DELTA OF THE GANGES AND BRAHMAPOOTRA)

Mud-flats.—Extent not mentioned.

Salt marshes.—Extent indicated on the map by means of the tidal channels (see reference later). The fresh-water swamps of the delta are protected from the sea by a chain of sandy islands, separated from each other by tidal channels and known as the *Sunderbuns*, the name evidently signifying severed mounds. This chain of islands averages 58 miles wide, but only the outer half is markedly cut up by tidal channels. Therefore it seems probable that the present tidal flooding extends some 30 miles inland, and the inner portion may have been built at an earlier date. Tidal effects on rivers are of course felt much farther but do not flood wide stretches of their banks.

TIDE 40 TO 70 FEET (BAY OF FUNDY, BASIN OF MINAS)

Mud-flats.—Widest in protected heads of bays. In the basin of Minas, estimated by J. A. Bancroft to average 0.75 mile wide. Along sides of the bay the current of from 6 to 8 miles per hour keeps the channel deep and open, and the sides scoured clean.

Salt marshes.—Shaler speaks of the dominance of the mud-flats over the upper marshes, and the rapidity with which the latter are built up by sediment thrown down at flood-tide when obstructions are built across the tidal marshes. Lyell speaks of thousands of acres having been reclaimed in this way.

REFERENCES

United States Coast:

United States Coast and Geodetic Survey Charts.

Indus Delta:

C. W. Tremenheere, *Journal of the Geographical Society*, Vol. XXXVII (1867), pp. 76, 81, and plate.

Ganges Delta:

James Fergusson, *Quarterly Journal of the Geological Society*, Vol. XIX (1863), plate, pp. 352, 353.

Basin of Minas:

Charles Lyell, *Travels in North America*, Vol. II (1855), p. 166.

N. S. Shaler, "Sea Coast Swamps of Eastern United States," *Sixth Annual Report* (1885), United States Geological Survey, p. 368.

J. A. Bancroft, "Ice-Borne Sediments in Minas Basin," *Proceedings and Transactions*, Nova Scotian Institute of Science, Vol. XI (1905), Part I, p. 161.

From the preceding facts a number of principles governing the development of the littoral zone may be drawn.

With lunar tides of less than 2.5 feet storm tides become of greater importance. The development of extensive mud-flats and salt marshes takes place in protected places. In exposed places the cutting action of the waves prevents either from forming. Mud-flats exposed at low tide become conspicuous with tides of about 6 feet range. When the tide is 10 feet, these may form belts a mile wide, but broken up by tidal channels. With higher tides there is but little tendency to increase the width of exposed flats, but the material constituting them may become coarser, the Gallegos River in Patagonia, where the tides reach 46 feet, showing lower flats composed of gravels and even of coarse bowlders.[1] With the larger tides the tidal channels for draining the tidal marshes are wide and deep, forming convenient protected passages for the larger vessels through silted-up estuaries or behind the barrier beaches.

The salt marshes are built up to near the upper limit of tidal flooding. Where storm tides are the most important the system of drainage of these marshes is very imperfect. With tidal range of from 4 to 6 feet this becomes developed, and with a range of from 10 to 16 feet they become rivers in size, capable of quickly leading an immense volume of water into the limits of the tidal area, but more important for quickly draining the tidal grounds during the ebb. The width of the salt marshes appears to be less dependent

[1] J. B. Hatcher, *Princeton Patagonian Expeditions*, Vol. I, Fig. 33, and p. 239.

upon the tidal rise than upon the greatness of the river and its delta which faces the tidal wave. This may be due to the great quantity of sediment furnished to the sea by the rivers, swept back by the tide and dropped at its flood, or to the subsidence which frequently characterizes such areas and which tends to drown the seaward end of the delta. Probably both causes contribute. This is illustrated by noting that on the Mississippi delta this width of marsh is 27 miles, while in Mobile Bay near by it is from nothing up to 2 miles. At Boston the marshes average less than a mile in width, while the Indus delta, with the same tidal range, shows them at least 17 miles wide. The delta of the Ganges in the presence of a tide of 16 feet is flooded by the tides for a distance of 30 miles, while in the Bay of Fundy and the Basin of the Minas the salt marshes average less than a mile in width.

The conclusion is geologically of some importance. The broad development of a littoral zone is largely independent of tidal influence, since, where the tides are small, oscillations of level through storms may develop it to practically the same width. The topographic character of the littoral zone, as indicated by dominance of mud-flats, size of tidal channels, etc., is, however, dependent upon the tidal range as one factor. Where the land is shelving, as along the eastern and southern coasts of the United States, the shore may be much broken with estuaries, but the land and the water are separated by a littoral, which, including both its upper and lower portions, does not average more than a mile in width. The littoral is therefore of insignificant area compared to the breadth of the coast plains on the one hand, and of the shallow sea on the other.

The littoral becomes broadest where a great quantity of sediment is poured into the sea by a great river and a contest ensues between the sea and the land. But in such places the river, if sufficiently powerful, builds out a land surface delta in the face of the storms and tides, while the undertow of the latter builds out another extensive platform, submerged in gradually deepening water, and ending where a depth is attained of from 50 to 100 fathoms. Even beyond this limit important quantities of the finer sediment are swept, forming occasionally bottom deposits from 200 to 800 miles from land.

It is seen, therefore, that in places where the littoral attains a maximum width of 30 miles there are at the same time far greater areas receiving land and ocean sediments, so that the proportion of the littoral zone is hardly greater than before.

These few places where the littoral attains a maximum width are offset by the thousands of miles of coast-line where the sea is cutting into the land, and the tide rises and falls against a narrow beach at the foot of a sea-cliff; so that the previous conclusion may be further extended to include all continental coast-lines; and it may be stated that, taking the world as a whole, the width of the littoral zone does not average a mile, and therefore comprises but a small fraction of the earth's surface compared with the great extent of marginal marine and even of continental deposits.[1]

With respect to the shallow-water marine formations this remains true under all geological conditions, and therefore remains true for all geological time. But occasionally, in periods when the continental surfaces were physiographically old, of greatly diminished area and supplying but little sediment, continental deposits may well have sunk to less importance than the littoral. During such periods, however, there is a corresponding expansion of epicontinental marine sediments, though at such times of a calcareous character, so that the insignificant proportion of the littoral to the sum-total of other sediments deposited upon the continental platforms would not be greatly changed, and has been a constant feature of the earth's surface.

CAUSES RESTRICTING THE WIDTH OF THE LITTORAL ZONE

The previous examination of open sea and estuarine coasts shows that the width of the littoral is not dependent merely upon the flatness of the shores, nor upon the magnitude of the tidal range. These, while contributory factors, can operate only within certain limits. In order to see why this is so, it may be well to state briefly some of the causes which influence the result.

1. The influence of varying slope of shore may be seen in Fig. 5.

[1] Chamberlin and Salisbury, *Geology*, Vol. I, p. 352, give the width of the littoral zone as half a mile, the length of the coast-lines of the world as 125,000 miles, and consequently the area of the littoral zone as 62,500 square miles, as against 10,000,000 square miles for the area of the shallow-water zone within the 100-fathom line.

Suppose that the shore, to begin with, is a smooth, gently inclined plane, represented in cross-section by *OB* or *OC*. The level of low tide being *OD*, the volume of water passing *O*, the lowest part of the littoral, will be represented in the one case by the triangle *OAB*, in the other by the triangle *OAC*. But the areas of these triangles are to each other as their bases *AB* and *AC*. Hence in this ideal

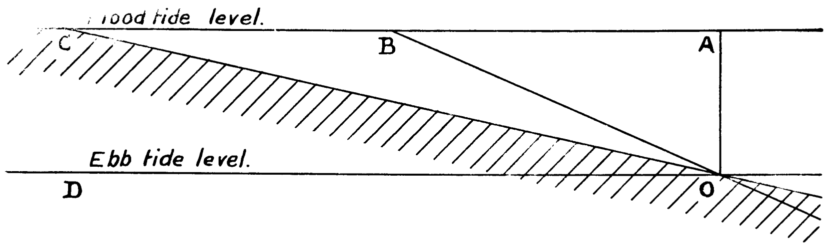

FIG. 5.—Diagrammatic relation of the width of the littoral zone to unadjusted slope of land surface.

case the volume, and consequently the mean velocity, of water flowing past *OA* will vary directly with the width of the littoral zone. But Révy has shown that the average velocity is an arithmetical mean between the bottom and surface velocities, and that the swifter the current, the more nearly the bottom velocity approaches the mean.[1]

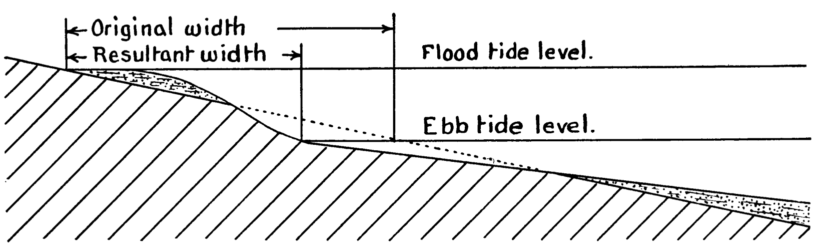

FIG. 6.—Diagram of littoral zone adjusted to slope, wave work neglected.

Therefore the bottom velocity increases somewhat faster than the width of the littoral in the ideal case. But the eroding ability of water varies as the square of the bottom velocity and the transporting ability as the sixth power. On an originally flat shore the mid-tide would consequently possess such scouring power for some distance on each side of the original low-tide limit that, as shown in Fig. 6,

[1] *Hydraulics of Great Rivers* (London, 1874), p. 147.

the bottom would be cleaned out, part of the detritus swept to the upper tidal limit and deposited, while a larger and coarser part aided by the downward grade would be swept seaward by the ebb-tide.

In nature the land slope is never smooth, and the discharge of the ebb-tide is concentrated along those lines which give the quickest egress and the greatest depth of water, the result being the building up of tidal marshes in protected places, the scouring of tidal channels, and the formation of extensive flats chiefly below the level of low tide. In these ways an originally widely extended littoral zone would be narrowed to a certain stable width for a given height of tide. The above discussion neglects the action of waves, chiefly operative at the upper and lower tidal limits, in exposed situations.

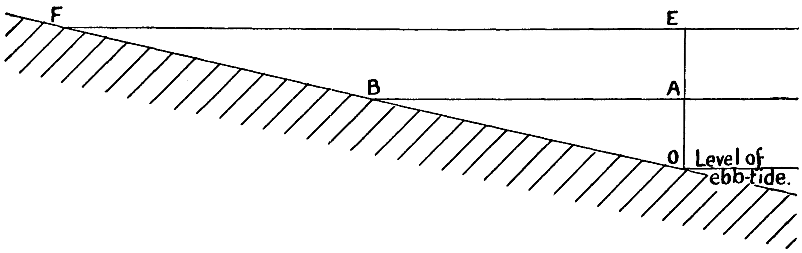

FIG. 7.—Diagram to illustrate relation of littoral zone and tidal scour to height of tide.

2. The influence of varying height of tide may be seen in Fig. 7. Letting AB and EF be the respective upper limits of tides on a recently invaded shelving shore: the volumes of water flowing past the low-tide limit will be as the areas of the two triangles OAB and OEF. But these being similar, the ratio of the areas will be given by the ratio of the squares of similar sides. Consequently, the volume, and with it the mean velocity, of the water invading the shore varies at the line OE as the square of the height of the tide, OA or OE. But Révy has shown that as the depth of a current increases the bottom velocity approaches more nearly the mean velocity, until in great depths and in strong surface currents they are substantially alike.[1] *Therefore on an ideal newly formed shore the bottom velocity past the point of low tide will increase somewhat faster than the square of the height of the variable tidal rise.*

[1] *Op. cit.*, p. 148.

The result as observed in nature is an added scour in regions of high tides by which the bottom is cut away, tidal marshes at the heads of bays or other suitable places are built with great rapidity, and these are dissevered from each other by tidal channels draining the marshes, which in the more striking cases may be sufficiently deep and wide even at low tide for the purposes of commerce. In time, if subsidence does not take place, the tidal marshes become raised by accretion through æolean and organic action until reclaimed from the sea, and the littoral zone is diminished as before to a certain stable width.

CONDITIONS FOR PRESERVAL OF THE SEDIMENTARY RECORD

It has been seen that in the making of the sedimentary record but an insignificant portion would be contributed by the littoral zone. There are still, however, two factors to be considered—that of the preserval of the record, and that of its ultimate exposure to observation through partial erosion.

In order to become part of a permanent geological record, the sedimentary structures must be preserved without obliteration, first, until buried and lithified, and, secondly, indefinitely protected from erosion until some new cycle of activities proceeds to destroy it and while so doing transitorially exposes it to observation.

PRESERVAL OF THE CONTINENTAL AND MARINE RECORDS

In regard to the river sediments, slow subsidence of the region or elevation of an adjoining region is necessary for their continual formation. Each layer of sediment from the flood waters is laid down upon the previously dried and hardened layer, and there is therefore not much tendency to erase the record made on the previous surface except in the lines of the channels. Soil beds, swamp deposits, mud-cracks, and ripple-marks are consequently abundantly recorded in fluviatile formations. Unless, however, subsidence carries at least the basal portions of the deposits below the ultimate base-level of erosion, the formation will be finally destroyed, as is illustrated by the present erosion of the Tertiary river deposits of the Great Plains facing the Rocky Mountains. In river deltas, however, the proper conditions are observed to occur. Here the upper limits are but

slightly above the level of the sea, and subsidence in such regions is observed ordinarily to go forward with accumulation. This will indefinitely protect the formation until some new and adventitious geological activity reverses the processes which resulted in the accumulation.

To sum up, then, it is seen that the geological processes which result in the accumulation of desert deposits, if carried to their limit, will ultimately destroy those same deposits, as Passarge has recently shown.[1] The same is apt to be largely true of Piedmont plains of river deposits; but in the case of interior basins, and more especially in deltas, the conditions are most favorable both for temporary and ultimate preserval of the land-surface record.

The same is, of course, true of the record made on the ocean bottom, since this is normally the region of deposit and not of erosion.

CONDITIONS FOR PRESERVAL OF THE LITTORAL RECORD

In regard to littoral deposits it will be seen, however, that the chances are frequently unfavorable for the preserval of its deposits until burial.

1. On an emerging land, such deposits would form a surface veneer and be the first layer to suffer erosion, before even a chance for lithification had occurred.

2. On a stationary or slightly subsiding coast, where delta deposits are encroaching upon the sea, the fresh-water material will fill up the estuaries and lagoons, covering and preserving their records, and crowding the beaches farther out to sea. The littoral deposits in that case would be preserved as old beach, lagoon, and estuarine deposits transitional, in a vertical section, between the off-shore marine deposits below and the fresh-water land-surface record above.

3. Where an old land surface is slowly subsiding, the weak erosive power of the upper portions of the rivers is no longer able to supply sediment for building out deltas against the sea, and there is, on the contrary, a transgression of the sea across the land. Assuming that the land surface slopes gently seaward, the depth of the littoral deposits behind the barrier beach where such exists cannot in general

[1] "Rumpfflächen und Inselberg," *Zeitschrift der deutschen geologischen Gesellschaft*, Vol. LVI (1904), Protokol., 193–209; review by W. M. Davis, *Science*, Vol. XXI (1905), p. 825.

be as great as the depth of the sea in front. The advancing sea will therefore tend to cut away and destroy whatever littoral deposits may be made in advance of it, as illustrated in Fig. 8*A*. Observations confirming this statement may be occasionally made along a subsiding coast, as that of New England. To illustrate, Boston is found to be sinking at the rate of a foot a century and New York City, according to the most recent estimates, at the rate of 1.5 feet per century.[1]

That the coast between the two cities participates in this movement is indicated by the sharp boundaries of the salt-water marshes.

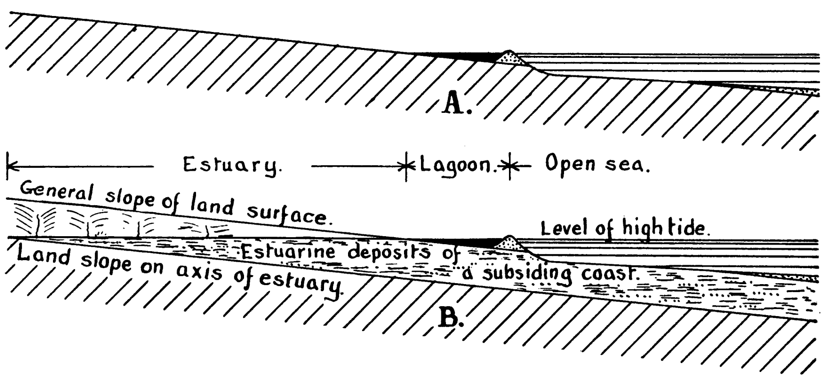

FIG. 8.—*A*, diagram illustrating progressive destruction of littoral deposits by marine planation over a subsiding land. *B*, cross-section on line of an estuary, illustrating part preserval of estuarine deposits during the transgression of the sea over a subsiding land.

These extend sharply to old alluvial slopes which rise at gentle angles from beneath them without any belt of fresh-water meadow being found between. If the land had been stationary for many centuries, the wash from the land, aided by the sediment from the highest tides, would have raised the border somewhat above the salt-marsh level. The opposite condition of affairs indicates therefore continual subsidence, but at a rate so slow that the organic and inorganic detritus, held by the roots of the marsh grass, is able to accumulate with sufficient rapidity to keep the surface at about the level of mean high tide.

A particular instance where the beach may be observed cutting

[1] G. W. Tuttle, *American Journal of Science*, Vol. XVII (1904), pp. 333–46.

away the older lagoon and marsh deposits may be cited from unpublished observations of Mr. I. Bowman. This is 2.5 miles south of Scituate Harbor, Mass., between the third and fourth cliffs, where the beach has retreated inland from 225 to 300 feet since 1898. The beach ridge is of pebbles, from 100 to 125 feet wide at mid-tide and from 8 to 10 feet above the level of the salt marsh behind it. In consequence of the rapid retreat, the marsh material at present shows at mean and low tide on the *seaward* side of the beach, illustrating the tendency of the sea to cut away the littoral as it advances upon the land.

There are a couple of ways, however, by which littoral deposits may be preserved upon a subsiding flat land. The first is illustrated by the unequal beach-cutting observed along the New Jersey coast.

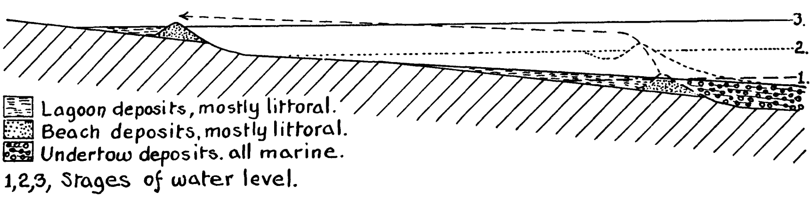

FIG. 9.—Cross-section illustrating occasional preserval of littoral deposits by building up of a beach, stages 1 and 2, without landward movement during land subsidence.

At Long Beach the sea has cut the lagoon space entirely away and is fronted by bluffs. Farther southward the barrier beaches begin and shut off Barnegat Bay. There is known to be a lateral transfer of beach material southwestward along the Atlantic coast. By this means it is possible for an offshore beach to be built up vertically as the coast subsides, the lagoon space behind broadening and deepening, as shown in Fig. 9. Finally, when the lateral supply of material ceases through recession of the bluffs, the beach will be rapidly transferred inland, but the depth of wave-planation may not reach to the bottom of the marsh deposits.

Again, the shore will be more or less indented with shallow river valleys turned into embayments or estuaries, and in these a greater depth of littoral and estuarine deposits may accumulate, and partly escape the marine transgression and planation which ensue with further subsidence. The protective effect will be slightly diminished,

however, by the incurving of the spit-bars thrown partly across the mouth of the estuary. Illustrations of this nature are well exhibited along the Atlantic coast of the United States. As seen in cross-section, the bottom line of Fig. 8*B* represents the center line of the estuary bottom, while the depth of the marine planation is determined by the average slope of the land.

In the sedimentary record made, therefore, upon a subsiding land, only a fragmentary littoral record should be preserved at the base, and upon tracing the formation laterally there should be frequent places where the marine off-shore sands, gravels, or conglomerates should rest directly upon the old land surface. This contact of true

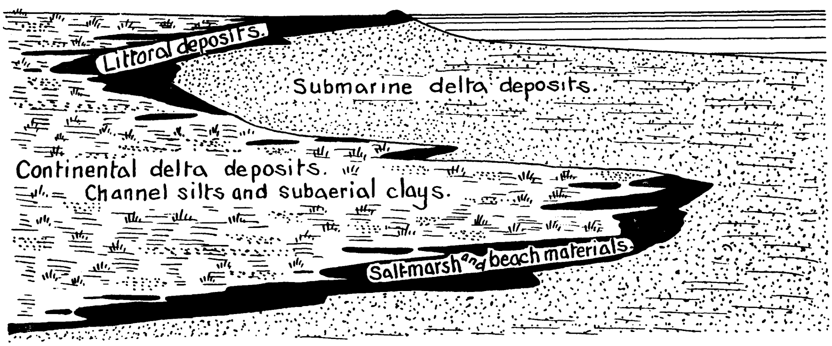

FIG. 10.—Ideal cross-section of a delta, showing geological relations of fluvial, littoral, and off-shore deposits. Vertical scale much exaggerated.

off-shore marine deposits with the old land surface seems to be the common rule observed upon that most striking of American transgressions, that of the middle and upper Cambrian, across the greater portions of the North American continent, though Dana[1] states that the beds "are in part beach made and wind made sandstones, ... and the layers often bear ripple-marks, shrinkage cracks, worm burrows, and, in some places, tracks of animals." The shrinkage cracks may doubtless be taken as good evidence in this instance of a littoral origin.

To sum up, it is to be expected that littoral deposits should be found dividing former land surfaces from sea bottoms, commonly present where the land surface is represented by subaërial delta

[1] *Manual of Geology*, p. 464.

deposits and comprises the *overlying* formation; frequently absent where the old land surface, ordinarily a land erosion surface, *underlies* the marine deposits. The littoral zone is small in local area compared with the occasional delta deposits which border it on the one hand, and the universal marine deposits which border it on the other. As seen in vertical section, therefore, the littoral deposits should have but limited lateral development on any one horizon. If the movement has been the subsidence of an old land, they should not be again encountered in the superior strata, but in the case of the contact of a delta with an epicontinental sea the littoral zone, as shown by the diagram, Fig. 10, might move backwards and forwards as a zigzag line through the vertical section, representing the advance and retreat of the sea as the subsidence on the one hand, or delta-building on the other, dominated at the moment, the littoral deposits dividing the marine from those made upon the surface of the land.

RELATIONS OF CONTINENTAL AND MARINE SEDIMENTATION THROUGH GEOLOGICAL TIME

In the preceding discussion the relative importance in area and volume of modern land, seashore, and shallow-water marine deposits has been discussed. It has been seen that the littoral zone occupies the least area and stands the smallest chance of preserval, while land deposits of various sorts hold second place; most important among these, on account of their favorable chances for preserval, being river sediments, made in interior basins, or as deltas encroaching upon the sea. The marine detrital deposits of the continental margins are, however, the most widespread and important of the three classes.

In discussing these relations they were seen to be dependent upon many broad features, such as the degree of continental uplift and areal extension, recency and magnitude of mountain movements, climatic zones, and other such factors. These have varied widely, however, through past time, and while the geographic details of former ages are largely wanting, still the general character of the terrestrial surface is in a manner known; as, for example, it is known that the Triassic over every continent was in general characterized

by broad continental uplift, orogenic movements, and variegated climates, while the Jurassic was, on the contrary, characterized by a spread of epicontinental seas, less rugged and elevated land-masses, and warm, equable climates extending into the polar regions. This conception of world-wide conditions characterizing the several ages, and distinguishing them from each other must, according to Chamberlin, form the ulterior basis of time-divisions and the classification of geologic history. But if the several ages have been characterized by certain relations of mountains, plains, and seas, then they should also be characterized by the kinds of deposits made under these conditions. The most natural method of testing this question would be to study all of the formations of the world belonging to a certain age, and group them according to area and origin. This has been done, and it is the method by which the conclusions in regard to the broader features have been arrived at. But as the very subject under discussion involves the possible confusion of certain unfossiliferous littoral and shallow-water marine deposits with those made upon the land, this method must be reversed, and by basing the arguments upon the known continental relations, as determined by formations in regard to which there is no doubt, conclusions may be reached in regard to the relative importance of deposits of those three classes which should characterize the different ages. This may be of value in suggesting discriminations not otherwise thought of, but it is not the purpose to offer here criteria for finally and definitely testing the origin of any particular formation. The latter question must, of course, be finally settled by a detailed study of the formation in the field and in all its aspects.

As introductory to this discussion it may be well to restate briefly certain of the principles which are found to govern the development of several classes of deposits at the present time.

Where young and lofty mountain ranges stand sharply above the surrounding country there will be much local waste on the Piedmont plains at their feet. If at least one slope faces the interior of a continent, this will result in extensive continental deposits, perhaps accentuated by conditions of aridity. Down-warped interior basins may also receive deposits. For effective delta building, however, there must be a submerged continental platform, or epicontinental

seas, and Chamberlin has pointed out[1] that the effect of the greater earth-movements has been to temporarily reduce to a minimum these shallow submerged portions of the continent. Such movements of continental uplift, or rather down-sinkings of the ocean basins, seem, however, to carry up portions of the crust to heights notably above the plane of isostatic equilibrium, from which they gradually settle back toward equilibrium by virtue of the slow fluency or quasi-fluency of the rocks.[2] At the same time, base-leveling is proceeding from the margins of the continents, reconstructing new coastal shelves, whose edges tend to become submerged both by the slight filling of the sea with sediment and by the settling back of the continental platforms. Assuming the truth of these general laws of major earth-movements, subaërial delta-building encroaching upon the shallow seas would attain greater importance as the erosion verged toward maturity, since the amount of landwaste increases; the streams, now being graded, carry it through to the shores, and submerged continental platforms have had time to form. At the same time, the deposits of arid interior basins and of Piedmont slopes will diminish in importance, and finally become more or less eroded.

Finally, as the continent becomes topographically old, the mountain slopes become subdued, the burden of the rivers lessens, they can no longer build out extensive deltas against the seas, noteworthy land deposits no longer form, and slight elevation of the ocean sursurface will cause it to widely transgress the base-leveled land.

Turning to the marine deposition of mechanical sediments, they should be observed to immediately increase in volume following continental uplift, several chief types being noted according to the nature of the land and the movement of uplift. If from a near-by mountain range, the sediments will be coarse in nature and formed through rock disintegration more largely than through decomposition. If from an older coastal plain, the marine deposits will comprise siliceous residues from a previous period of erosion. If from a decomposed regolith of a former near-by low-lying land, the sediments will be

[1] The Ulterior Basis of Time Divisions and the Classification of Geologic History, *Journal of Geology*, Vol. VI (1898), pp. 449–62.

[2] *Ibid.*, p. 455.

marked by an abundance of leached argillaceous and ferruginous silts discharged at numerous points along the coast. If from a distant mountain system, the material will be similarly fine-grained, but will show less decomposition and leaching, and be discharged in great quantity by great rivers at a few widely distant points. Thus there are a variety of types of marine sedimentation, the material becoming more uniform in character and more widely spread over the growing circum-continental shelves as the erosion passes into the stages of maturity. Finally, with old age the amount of mechanical detritus greatly lessens, the conditions for limestone formation approach near to the shores, but greensands and the limy shales are still indicative of the presence of land-waste long after all *subaerial* detrital deposits have ceased to form.

Even in old age, however, it is still possible that slight regional uplifts and warpings may result in a temporary renewal of rapid erosion, since under such circumstances the regolith will have formed a deep and voluminous mantle to the continent, readily removed and swept to sea upon the least rejuvenation of the rivers. If the movement is accompanied by an adjacent down-warping in a continental interior, the deeply decayed rock mantle may be swept into it and be built up by river aggradation as a continental deposit, which further warping may carry beneath the sea.

GENERAL APPLICATIONS TO GEOLOGICAL HISTORY

Having sketched these outlines of the relations of continental and marine sedimentation to the broad earth-movements which have separated and individualized the geological ages, it will be in order to apply them, by way of illustration, to certain typical periods. It will be seen that they suggest, though they do not prove, rather different interpretations for certain formations from those which have been ordinarily held.

Pre-Cambrian æon of continental extension.—It is a matter of familiar knowledge that nearly everywhere the marine deposits of the Cambrian lie upon a far older and unconformable basement. Occasionally the Cambrian appears to have a downward unfossiliferous extension, as in the southern Appalachians, or sometimes rests unconformably upon older, usually barren sediments, but little

or no more metamorphosed than itself, as in Montana and in Arizona. More frequently, however, over all the continents it rests directly upon steeply dipping gneisses and schists. These structures, characteristic of the zone of rock-flowage, indicate widespread and profound erosion previous to the Cambrian transgression, and therefore a period of wide and long-enduring continental extension.

The usual concept of the development of the North American continent embodied in the textbooks of the past begins with the widespread submergence of the late Cambrian and early Ordovician. From that stage Dana has long since shown how the continent through the Paleozoic gradually, and with many regressions, gained in dry land.

Walcott considers, however, that the prevailing view of the geographic distribution and extent of the continental area at the beginning of Paleozoic time is too restricted, and that the continent was larger at the beginning of the Cambrian period than during any subsequent epoch of Paleozoic time.[1] At this date (1891) Walcott had not yet separated the underlying belt formation of Montana from the Cambrian, and consequently considers this portion of the Northwest to have been beneath the sea during Lower Cambrian time. With the discovery of an uncomformity separating the Belt from the Middle Cambrian,[2] this statement in regard to the extent of the early Cambrian land is further justified, and will probably be considered by those familiar with the subject as very conservative.

LeConte also emphasizes the significance of the Pre-Cambrian record of erosion, the subject being briefly stated in his *Elements of Geology*.

A truer appreciation of the facts of the world-wide Pre-Cambrian unconformity may finally lead to the erection of this Pre-Cambrian period into an æon of continental extension as widespread and as long-enduring as that of the Mesozoic and Cenozoic.

Yet it is only the end of this period, as marked by the Lower Cambrian unconformity, which is known with any accuracy. On going backward in time, evidences of repeated orogenic movements

[1] "The North American Continent during Cambrian Time," *Twelfth Annual Report* (1891), U. S. Geological Survey, Part I, p. 562.

[2] C. D. Walcott, "Pre-Cambrian Fossiliferous Formations," *Bulletin of the Geological Society of America*, Vol. X (1898), p. 210.

are encountered widely separated in time, deforming older basins of sediments, and resulting in erosions and unconformities. It is not to be implied, therefore, that such formations as the Belt of Montana and the Grand Canyon terranes, because they lie immediately below the Middle Cambrian, were necessarily deposited in an *immediately* Pre-Cambrian period.

From the thickness of their detrital accumulations situated in the interior of the continent, they probably belong to interior basins of subsidence within rather wide land masses. That these basins were, at least during a part of the time, connected with the open sea is shown by limestone formations, thousands of feet in thickness, which they contain.

In the Lewis and Livingston Ranges Willis has measured a thickness of the Algonkian of about 10,000 feet, without either the upper or lower limits being visible. Of this from 4,500 to 5,300 feet are argillites and quartzites, while 5,400 feet are limestones, divided into two great formations.[1]

Near Helena, in west-central Montana, Walcott has estimated the total thickness of the Belt terrane at 12,000 feet, of which 7,600 feet consist of argillites and quartzites, the remainder, as before, being divided into two great limestone formations.[2] This region is possibly not far from the limits of the original basin during much of the time of deposition, since the Belt formations disappear from between the older gneisses and the younger Cambrian some 60 miles to the south.

In the Pre-Cambrian Grand Canyon series, exposed in northwest Arizona, Walcott gives the Unkar and Chuar terranes a combined thickness of 11,950 feet, of which about 400 to 500 feet are limestones, and about 1,000 feet lavas. The remainder are sandstones and argillites.[3]

In view of these great thicknesses of sandstones and argillites accumulated in interior basins of Montana and Arizona at a time of at least considerable continental extension, the hypothesis of a subaërial origin by river aggradation may well be held in mind as a possibility for certain formations, as well as the more common

[1] *Bulletin of the Geological Society of America*, Vol. XIII (1902), pp. 316, 317.

[2] *Ibid.*, Vol. X (1898), p. 204.

[3] *Fourteenth Annual Report*, U. S. Geological Survey, Part II, pp. 508–12.

hypothesis of the accumulation of such materials at the bottoms, or within the margins, of shallow seas.

Again, in the Lower Cambrian, according to Walcott, the eastern side of the narrow Appalachian trough appears to have been a bold and precipitous mountainous area. In the trough itself beneath the Olenellus sandstone occurs a great series of variegated shales.[1] These are of course no proof of land accumulation, but the geographic relations of land and water were such as to suggest the possibility that delta deposits may have been built out into a trough which later, by a slackening of erosion or a greater subsidence, allowed the region to pass from largely subaërial to marine conditions, the marine transgression being marked by the deposit of the Olenellus quartzites.

In conclusion it is suggested that the Pre-Cambrian and Lower Cambrian ages of wide continental extension offered conditions favorable for the accumulation of the several types of subaërial deposits, and that in the interpretation of the mechanical sediments of those times this possibility should be always held in mind. The presumed absence of a fossilizable land fauna and flora in the life of those periods would remove the possibility of proving a continental origin through such secure means.

Paleozoic epicontinental basins.—During the Eopaleozoic the continents became largely submerged, but in the Neopaleozoic partial emergence was the rule, varying from fairly extensive land conditions at times (in late Silurian and Lower Devonian), as has been shown by Ulrich and Schuchert,[2] to submergence possibly nearly as complete as that of the Ordovician. At times mountain-making forces and regional uplift operated on an extensive scale, as is witnessed, for example, by the enormous mass of Upper Devonian sediments along the northeastern portion of the Appalachian trough from which Willis computes that the uplift supplying these sediments corresponded in volume to a mountain range similar to the Sierra Nevada,[3] and the sediments deposited in the Old Red Sandstone

[1] "The North American Continent during Cambrian Time," *Twelfth Annual Report*, U. S. Geological Survey, Part I (1891), pp. 536, 551.

[2] "Paleozoic Seas and Barriers in Eastern North America." *N. Y. State Mus., Bull. No. 52*, pp. 633–663, 1902.

[3] *Paleozoic Appalachia*, Maryland Geological Survey, Vol. IV (1902), p. 62.

basins of the British Isles, Norway, and the Arctic islands to the north.

This mountain-building, taken into consideration with the restricted nature of the interior sea of eastern North America between the Cincinnati axis and the eastern border, forms geographic conditions which should favor the development of extensive deltas filling up shallow seas and giving rise to the formation of subaërial deposits. Turning to the strata themselves to find an answer to this suggestion, one notes the sparingly fossiliferous character of the Catskill group of the Upper Devonian and the fact that the few fossils found are those of fishes, Eurypterids (Stylonurus), and some fresh-water lamellibranches (Amnigenia), suggesting that, occasionally at least, subaërial deltas may have covered considerable regions, and should be looked for by a critical study of textures and structures. Many geologists would grant this possibility, though it has found but little recognition in geological literature.

That differences of view among able living geologists may be held upon the subject of the Paleozoic formations is indicated by the fact that Willis, as a result of his prolonged and detailed studies of the Appalachians, interprets the Tuscarora (Medina) sandstones of Maryland as submarine coastal plain deposits,[1] while more recently Grabau, in a preliminary paper, advances the hypothesis that the Siluric conglomerates and sandstones are part of a huge subaërial fan, whose apex was in southeastern Pennsylvania.[2]

This is not mentioned with the intention of urging the continental point of view, since the cleanly sorted character of much of the formation would seem to indicate to the present writer that prolonged sorting by waves, rather than the limited sorting and variable character of river work, had been concerned. It might well be, however, that an alternation of conditions has occurred, marine deposition dominating in one district, river work in another.

Of the Paleozoic formations it is in the coal-measures, however, that the relations between continental and marine deposits are most distinctly shown and most fully appreciated; largely because the climatic conditions were such as to lead to the formation of swamp

[1] *Op. cit.* (1902), pp. 55, 56.

[2] "Physical Characters and History of Some New York Formations," *Science*, New Series, Vol. XXII (1905), p. 533.

jungles whenever delta surfaces were exposed to the air without either uplift sufficient to produce erosion or subsidence sufficient to result in burial. With occasional exceptions, which may be due to river driftage, it is conceded that the coal was formed *in situ*, and thus each coal-bed becomes a determined land surface, although once in a swamp condition.

The analogy of the carboniferous swamps with those existing at present upon delta surfaces or buried beneath the later river deposits has been perceived and pointed out since the time of Lyell. This analogy, together with the usual absence of marine fossils and the occasional presence of land or fresh-water forms in the associated strata, has led to the well-founded belief in the chiefly fresh-water or brackish-water origin of the coal-measure shales and sandstones of Nova Scotia, the Pennsylvania anthracite basins, and other regions. But over the western portion of Pennsylvania and much of the continental interior, beds of limestone with marine fossils occur at intervals through the coal-measures, indicating in those regions periodic invasions of the sea.

From these facts it is inferred that periodic subsidences took place, allowing transgressions of the widespreading epicontinental sea across the submerged delta surfaces. But the absence of the limestones nearer the shore and in basins like that of Nova Scotia, where the great thickness of shales, sandstones, and conglomerates testifies to rapid erosion and sedimentation, indicates that subsidences did not allow the sea to reach this far inland, but that it was kept out by the rapidity of river aggradation, which, as the basin subsided, distributed mud, sand, and gravel *pari passu* over the old forest swamp. Thus, the same conclusion is derived inductively as that previously arrived at by deduction concerning the phenomena of a subsiding delta region, where it was concluded that the marine and continental portions should be broadly interfingered, the sea cutting in from one side, the rivers building out from the other, and the littoral being a relatively unimportant transition zone resulting from the contest between the two.

Statements might be quoted from able writers in which it is assumed that the subsidences were of an oscillatory nature, and that the reclamation of the land surface from the sea was due largely to

uplifts which would cause the sea bottom to just emerge above the sea-level when coal-swamps would form, while subsidences would carry it downward, maintaining depths of 100 feet or more during which sediments were being deposited.

Upward oscillations are, of course, not to be excluded, but in regard to the major cause of land-surface reclamation the following may be quoted from Geikie:

It has been assumed that, besides depression, movements in an upward direction were needful to bring the submerged surface once more up within the limits of plant growth. But this would involve a prolonged and almost inconceivable see-saw oscillation; and the assumption is really unnecessary if we suppose that the downward movement, though prolonged, was not continuous, but was marked by pauses, long enough for the silting-up of lagoons and the spread of coal jungles.[1]

LeConte emphasizes the same conclusion as to the cause of the alternation of strata; it being due not to crustal oscillation, but to the operation of two opposing forces, one depressing (subsidence), the other upbuilding (river deposit), with varying success.[2]

Dana also states that, when

under verdure, the surface must have lain for a long period almost without motion; for only a very small change of level would have let in salt water to extinguish the life of the forests and jungles, or have so raised the land as to dry up its lakes and marshes. Hence the grand feature of the period was its prolonged eras of quiet, with the land a little above the sea-limit.[3]

It is inconceivable that uplifts should have terminated and the land rested quietly almost indefinitely when it was brought exactly to the sea-surface, and it has been shown in the earlier part of this article that the sea and land always tend to be differentiated.

It is seen then that, supposing a small subsidence of, for example, 100 feet to take place, the river building would on the landward side keep pace with it. The coal-jungles would first be quietly flooded with fresh-water lagoons, as over portions of the Ganges delta. In these clays would be laid down, quietly burying and protecting the extinguished forest, and preserving within itself numerous fossils of ferns and leaves. Following this, the shifting river distributaries would deposit sand, or possibly even gravel, the whole

[1] *Text-Book of Geology*, 4th ed. (1903), p. 1018.

[2] *Elements of Geology*, revised ed., p. 390.

[3] *Manual of Geology* (1895), p. 708.

covered continually with sufficient vegetation to leach out by its decay the iron from the deposited sediments, but not standing in water, and therefore finally destroyed by oxidation.

On the seaward side the subsidence brings about a transgression of the sea with considerable erosion of the forerunning transitional littoral zone, or even of the underlying fluviatile and swamp formations, such as is sometimes observed to have occurred in the coal-measures of Illinois, Kentucky, and Missouri. In order to observe the process of land-reclamation by the river deltas from the sea, suppose, to continue the example, that the subsidence has been sufficiently rapid for the sea to gain 10,000 square miles from the land with an average depth of 50 feet, at which time the subsidence ceases.

The Ganges annually carries across its delta to the sea sufficient sediment to cover one square mile 221 feet deep; the Mississippi annually discharges into the Gulf of Mexico sufficient to cover one square mile 268 feet deep. Applying these figures to the hypothetical case, and assuming that one-half of the discharged sediment goes to make the fore-set beds by which the delta is built outward, it is seen that the Ganges would completely reclaim this area in 4,524 years, the Mississippi in 3,730 years. These, however, are two of the greatest rivers. But even if the carboniferous rivers discharging across the region of the Appalachian coal-fields delivered but a tenth part of the detritus borne to the sea by the Ganges and the Mississippi, it is seen that the transgressive effect of the supposed subsidence would be completely nullified in periods of 45,240 and 37,300 years. During this period of quiet and of land extension, conditions for the formation of coal would exist over much of the delta surface not actually traversed by the rivers, the swamps by the deposit of organic débris keeping pace to some extent with the distributaries raising their beds as the delta advances, and thus tending to prevent the wandering of the rivers across them.

In the present connection it is desired to emphasize not only the upbuilding but the outbuilding capacity of rivers, by which, if their sources are in highlands, their deltas may rapidly push into and fill up shallow epicontinental seas. Under such circumstances it is largely a question of the rate of river deposition and the volume of the sea to be filled.

In conclusion, then, it may be said that during the Paleozoic the eastern margin of the United States witnessed repeated uplifts and occasional mountain-making movements, which poured down great quantities of sediments into a shallow and at times restricted interior sea. These conditions should lead during times of rapid erosion to extensive subaërial deltas; sometimes temporary fresh-water marshes or periodically inundated desert flood-plains; sometimes verdure-covered swamps and plains: deltas showing great thicknesses of subaërial beds advancing to a considerable distance into the sea, alternating with periods of relatively more rapid subsidence or slackened erosion when the sea would transgress across the subsiding delta. At present the coal-beds, and the occasional presence of shells of fresh-water facies in the associated dark shales, are considered the only decisive evidence of such conditions, but the absence of coal-beds does not prove the contrary side of the question.

Mesozoic and cenozoic continental deposits.—The possibility of the occurrence of Mesozoic continental deposits has been widely recognized in both the New and Old World, especially for the closing stages of the Paleozoic and the opening of the Mesozoic, when the continents appear to have been broadly uplifted concomitantly with orogenic movements, and conditions of coldness and aridity occurred in many parts of the world, coldness and humidity in others. The conditions seem to have been of a somewhat similar nature to those recurring at the end of the Tertiary and enduring in a measure to the present time. It does not seem necessary, therefore, in the present connection to enter into a detailed discussion of the possibly or probably subaërial Mesozoic deposits of Europe, Asia, and America. Neither is it necessary under the present heading to discuss the deposits of the Tertiary and Quaternary still enduring at the surface, since it is the accumulated knowledge of these which has been used as the key and the test of this discussion, and it is by a further study of them that added light will be shed upon the past.

CORRECTION.—Through a printer's error the titles of Figs. 3 and 4 in Part I, pp. 347 and 349, were transposed.